Chapter 5
Development of Acceleration Time-Histories

5-1. Introduction

a. Purpose and scope. This chapter describes procedures for the development of site-specific acceleration time-histories of ground motions for seismic analyses of hydraulic structures throughout the United States.

b. Objective of acceleration time-history development. The overall objective in developing acceleration time-histories is to have a set or sets of time-histories that are representative of site ground motions for the design earthquakes(s) and that are appropriate for the types of analyses planned for specific structures.

c. Organization of chapter. Paragraph 5-2 provides an overview of the approach to and process of developing time-histories. Paragraph 5-3 describes criteria for the initial selection of acceleration time-histories. Paragraphs 5-4 and 5-5 describe two alternative methodologies for final development of design time-histories using the time-histories selected as described in paragraph 5-3. Paragraph 5-6 provides guidance for modifying time-histories for the response of local site conditions. Appendices B through D provide further details on various aspects of time-history development.

5-2. Overview of Approach for Time-History Development

This paragraph outlines the recommended general approach for developing acceleration time-histories for the seismic analysis of hydraulic structures. The process outlined below is described in greater detail in subsequent paragraphs of this chapter. The process is summarized in chart form in Figure 5-1.

a. *Initial selection of candidate time-histories*. Before time-histories are developed, design earthquakes and design ground motion characteristics are developed for the project. This process includes characterizing the tectonic environment of the site; characterizing the design earthquake(s) in terms of magnitude(s), distance(s) from the site, and other factors (e.g., type of faulting); characterizing the local site conditions; and developing design site ground motion characteristics for the design earthquakes. For the seismic design of concrete hydraulic structures, the design ground motion characteristics typically include smooth design response spectra (which also include the zero-period acceleration that is equal to the peak ground acceleration), duration of strong shaking, and special ground motion characteristics (e.g., near-source pulsive motions). Guidelines for the development of site-specific design response spectra of ground motions are presented in EM 1110-2-6050. Given these characteristics of the design earthquakes and ground motions, time-history records are then selected from the available database of recorded ground motions that are reasonably consistent with the design parameters and conditions. If sufficient recorded motions are lacking, simulated-recorded time-histories can be developed using ground motion modeling methods.

b. *Modification of time-history records and development of final sets of time-histories*.

(1) Although the time-histories are initially selected to be reasonably consistent with the seismic setting, design earthquake, and design ground motions, these time-histories and their response spectra may still differ substantially in amplitude from the design ground motion levels. This is because design ground motion characteristics are typically defined on the basis of statistical analysis of ground motion data, and these data

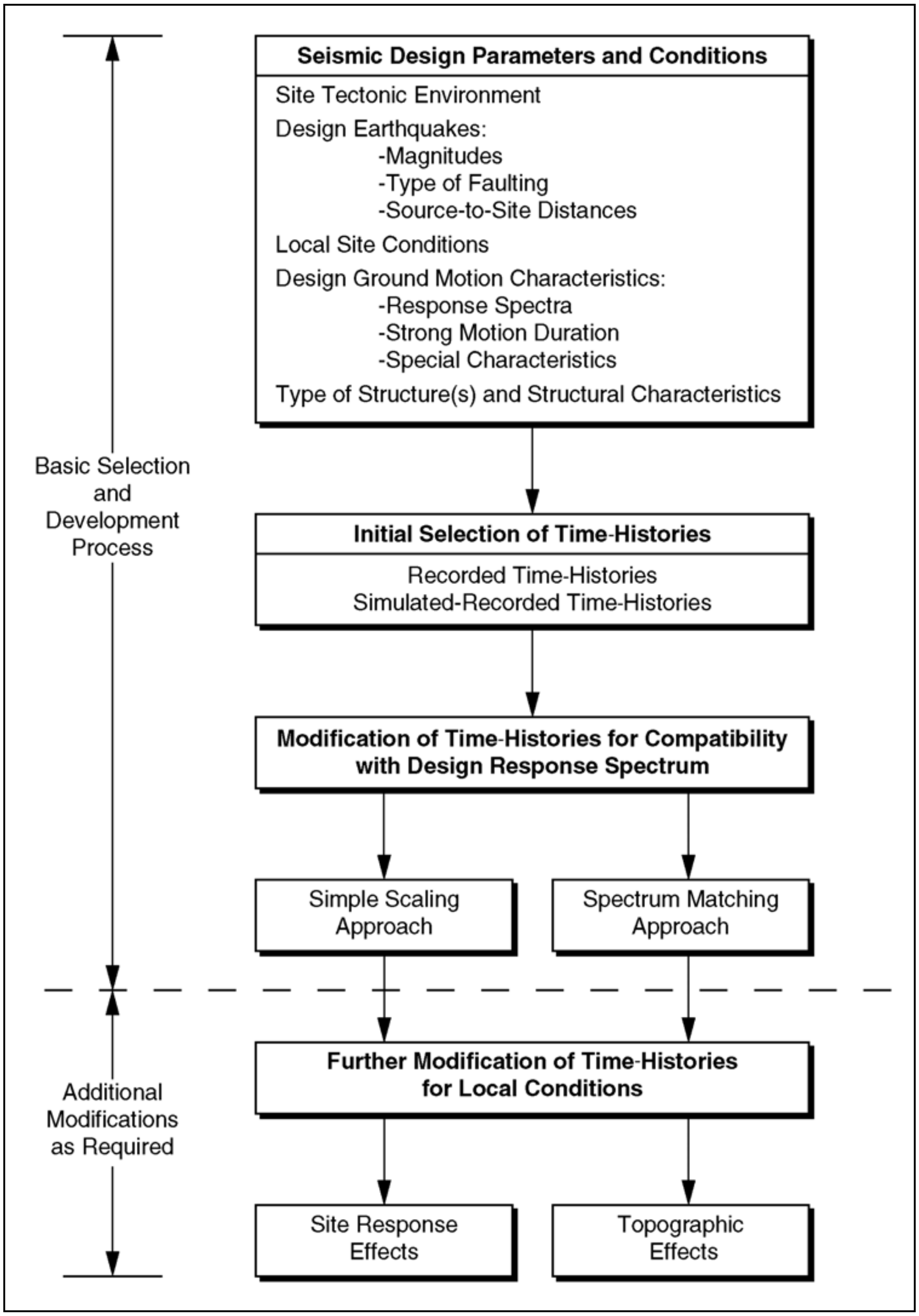

Figure 5-1. Process for developing time-histories for seismic analysis and design

exhibit considerable scatter. Therefore, any single ground motion record may have characteristics that lie above or below mean ground motions defined statistically for a given design earthquake.

(2) Two approaches may be used to adjust or modify the selected time-histories to be closer to the design ground motion conditions. In the first approach, the only modification to a given time-history is simple scaling (by a single factor) of the time-history so that its spectrum is at the approximate level of the design response spectrum in the period range of significance to structural response. Because the spectrum of any

recorded time-history has peaks and valleys, it is likely that this scaling will result in a spectrum that exceeds the smooth design spectrum at some periods and is lower than the design spectrum at other periods. Therefore, additional time-histories will probably need to be selected and scaled so that the spectra of the set of time-histories provide an aggregate match or fit to the design spectrum. In the second approach, a time-history is first scaled and its frequency content then modified so that its spectrum is a good match to the smooth design spectrum (spectrum matching approach).

c. Further modification of time-histories for local conditions. If time-histories in *b* above are developed for bedrock underlying a site and it is desirable to modify them for the overlying soil profile, then site response analyses may be conducted in which the rock time-histories are propagated through an analytical model of the site soil profile. Because it is usually assumed that the acceleration time-histories developed in *b* above are representative of ground motions on level ground, an analysis could also be considered to account for topographic effects at a site that has very irregular topography.

5-3. Initial Selection of Time-Histories

a. Use of recorded and simulated-recorded time-histories. When available for the parameters and conditions of a design earthquake, actual earthquake time-history records should be selected as the initial time-histories that are subject to further scaling or modification for use in seismic analysis. However, in some cases, few or no time-histories may have been recorded during earthquakes similar to the design earthquake. Conditions for which there are relatively few actual earthquake recordings include the following:

- Moderate- to large-magnitude earthquakes in the central and eastern United States.

- Large-magnitude (i.e., magnitude .8) shallow crustal earthquakes.

- Near-source, large-magnitude (magnitude $\geq$ 7) earthquakes (although the number of recordings for magnitude .6-1/2 to 7 earthquakes has significantly increased in recent years, and the number of recordings for magnitude >7 earthquakes has been greatly increased by the 1999 earthquakes in Taiwan and Turkey).

In cases where suitable recordings are lacking, consideration should be given to developing initial ground motion time-histories using theoretical (numerical) ground motion modeling methods that simulate the earthquake rupture and the source-to-site seismic wave propagation. The methods are being increasingly used to develop time-histories, especially where ground motion data are lacking. Appendix B summarizes the overall approaches involved in ground motion simulation and examples of the application of these approaches.

b. Selection criteria for time-histories. The selection of recorded acceleration time-histories should be guided by the following criteria:

(1) Tectonic environment. Candidate time-histories should have been recorded in a tectonic environment similar to that for the design earthquake. Within the United States the following tectonic environments are generally recognized as being somewhat distinct: shallow crustal fault earthquakes in the western United States (WUS); subduction zone earthquakes along coastal northwest California, Oregon, Washington, and Alaska; and earthquakes in the central and eastern United States (CEUS) (roughly east of the Rocky Mountains).

(2) Earthquake magnitude and type of faulting. Magnitudes of earthquakes generating selected time-histories should be close to (within approximately one-half magnitude unit of) the design earthquake

magnitude. The type of faulting (i.e., strike-slip, reverse, normal, oblique) for the earthquake preferably should be the same as that postulated for the design event, but this is less important than selecting time-histories from earthquakes of similar magnitude.

(3) Earthquake source-to-site distance. The source-to-site distances of earthquakes for selected time-histories should be similar to the design source-to-site distance. The preferred source-to-site distances for the selected time-histories should be within a factor of 2 of the design distance. However, for design source-to-site distances of less than 10 km, it is desirable to select time-histories recorded at distances from 0 to about 10 km in order to have near-source characteristics in the time-histories.

(4) Subsurface conditions. The subsurface conditions for the selected time-histories preferably should be similar to the project site condition for which design time-histories are desired (e.g., rock, deep firm soil). However, if a sufficient number of recordings for the same site condition are not available, records from firm soil sites can substitute for those recorded on rock and vice versa.

(5) Response spectrum characteristics of time-histories. Ideally, the response spectrum of an acceleration time-history selected for use in seismic analysis would have amplitudes similar to those of the design response spectrum. However, some amount of scaling of the time-history is usually required to bring its spectrum to the approximate level of the design spectrum. As a general guideline, it is desirable that time-histories selected for seismic analysis not require scaling upward or downward by more than a factor of about 2 to bring their spectra on average to the approximate level of the design spectrum in the period range of significance for structural response.

(6) Duration of strong shaking.

(a) The duration of strong shaking should be specified for the design earthquake. For the time-histories selected for analysis, strong motion duration should generally be within a factor of 1.5 of the duration specified for the design earthquake. It is more important that the duration not be underestimated than that it be overestimated. For prediction of strong motion duration on rock in the WUS, the correlation of significant duration with magnitude developed by Dobry, Idriss, and Ng (1978) and shown in Figure 5-2 can be used. The correlation is considered by the authors to be valid for the magnitude range of 4.5 to 7.6. The distance distribution of the data used by the authors suggests that the correlation is reasonably applicable within about 50 km of the earthquake source. An increase in duration with distance may be expected for greater distances. In Figure 5-2, the equation for the median prediction of duration is given; the standard deviation for the logarithm (base 10) of duration is equal to 0.13. In this correlation, duration is defined as the time required to build up from 5 to 95 percent of the integral

$$\int_{t=o}^{t=t_f} a^2 \, dt \tag{5-1}$$

where t_f is the total duration of a time-history and a is acceleration. Arias (1970) showed that this integral is a measure of the energy of an accelerogram. Figure 5-3 illustrates this definition of strong motion duration in the form of a Husid plot (after Husid 1969), which shows the buildup of the energy of an accelerogram with time and the time interval for 5 to 95 percent energy buildup. Duration on soil sites tends to be longer than on rock sites and is more widely scattered. Based on data presented by Dobry, Idriss, and Ng (1978), duration on soil sites may be approximated as 1.5 to 2 times the value estimated for rock sites.

(b) Lack of strong motion data has prevented development of a correlation similar to that in Figure 5-2 for the CEUS. Figure 5-2 and the characterizations discussed in the preceding paragraph may be used to approximately characterize the duration of strong shaking in the CEUS.

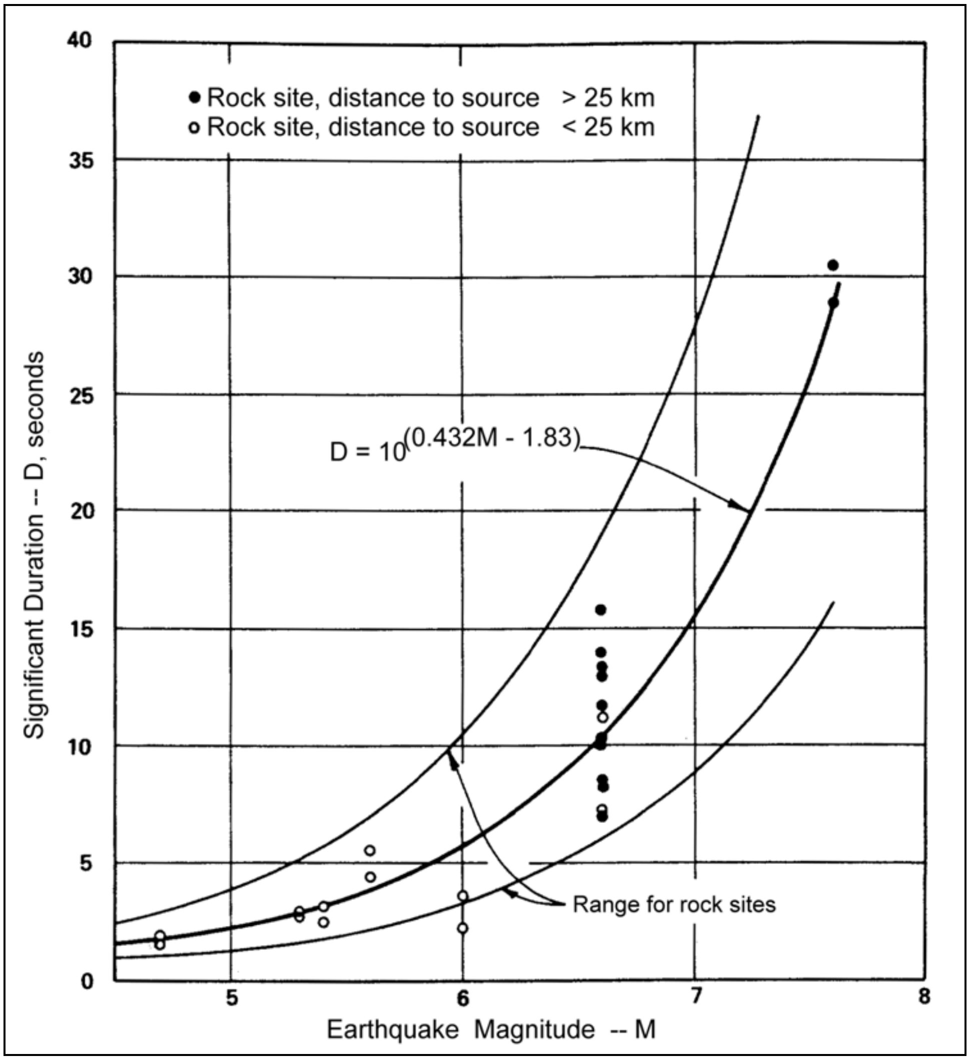

Figure 5-2. Correlation for duration of strong shaking on rock in the western United States (from Dobry, Idriss, and Ng 1978, courtesy of *Seismological Society of America*)

(7) Pulse characteristics and sequencing. No general correlations exist relating how the characteristics and sequencing of acceleration pulses vary with earthquake characteristics, distance, or site conditions. It is well known, however, that in the near-fault region, ground motion time-histories often contain a strong intermediate- to long-period pulse that is a result of the fault rupture process. Therefore, at least some of the acceleration time-histories used for design in the near-source region (i.e., within about 10 km of the fault rupture) should contain a strong ground motion pulse. It has also been found that this pulse is directional in nature, being stronger in the direction perpendicular to the fault strike (i.e., fault-normal component) than parallel to the fault strike (i.e., fault-parallel component) (e.g., Somerville et al. 1997). The ground motion pulse near faults is illustrated in Figure 5-4 for the Rinaldi recording obtained during the 1994 Northridge earthquake. Guidelines for characterizing the response spectral content of near-source pulsive ground motions are presented by Somerville et al. (1997). A limited amount of research has also been conducted on the time-domain characteristics of the near-source pulse; results are presented by Somerville (1998) on the period and peak amplitude of the velocity pulse.

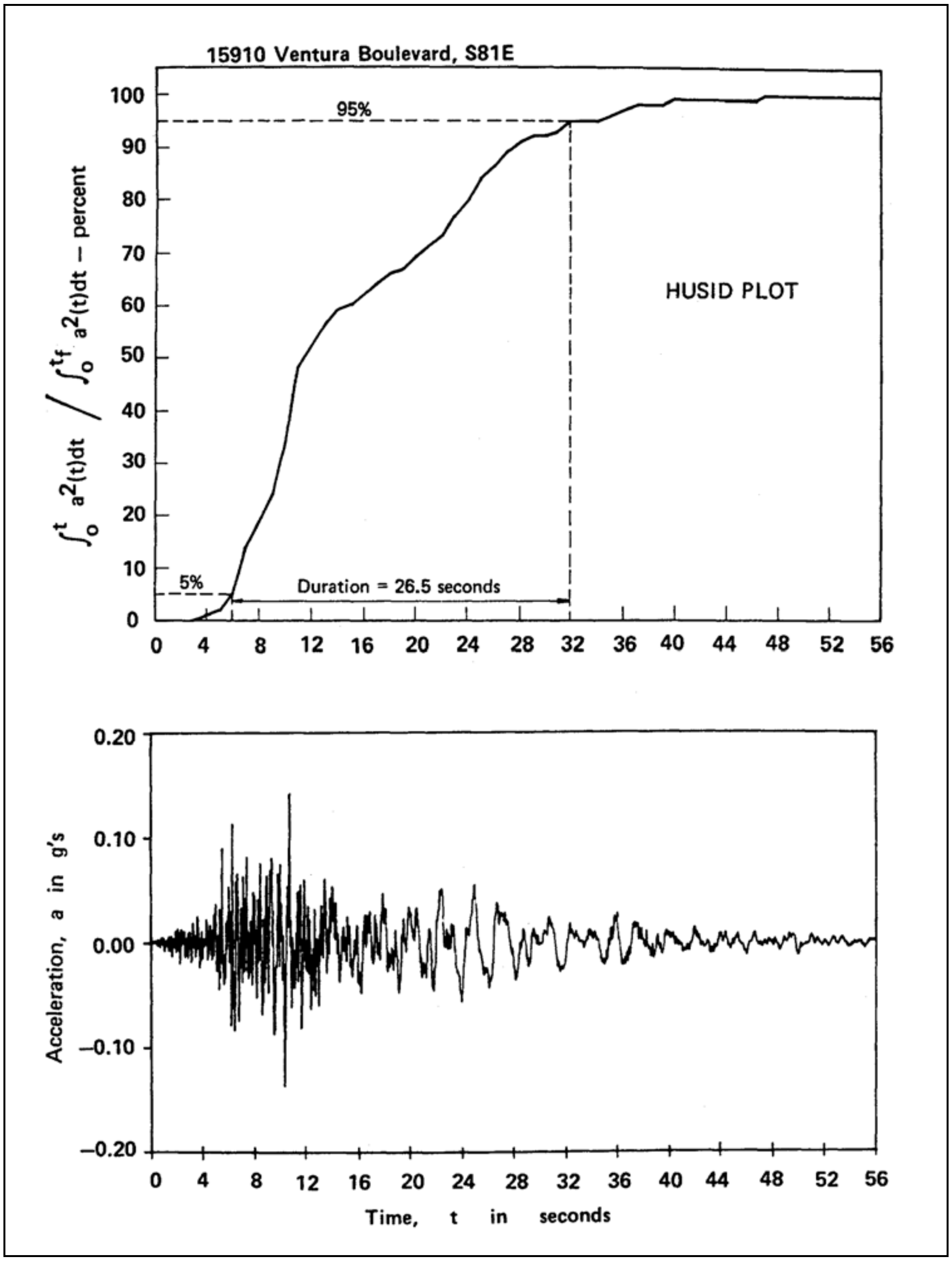

Figure 5-3. Typical Husid plot and duration as defined by Trifunic and Brady (1975) and Dobry, Idriss, and Ng (1978) (from Idriss 1979, courtesy of American Society of Civil Engineers)

c. Selection of records for deterministically defined and probabilistically defined earthquakes.

(1) Application of these guidelines is straightforward when design earthquakes are expressed deterministically, i.e., in terms of magnitude, faulting type, and source-to-site distance. However, the application of the guidelines is less straightforward when the design earthquake ground motions (typically the response spectrum) are derived from a probabilistic ground motion analysis (often termed a probabilistic seismic hazard analysis or PSHA). From this type of analysis, which is described in detail in EM 1110-2-6050, the design response spectrum for a certain selected probability of exceedance in a design time period (or, equivalently,

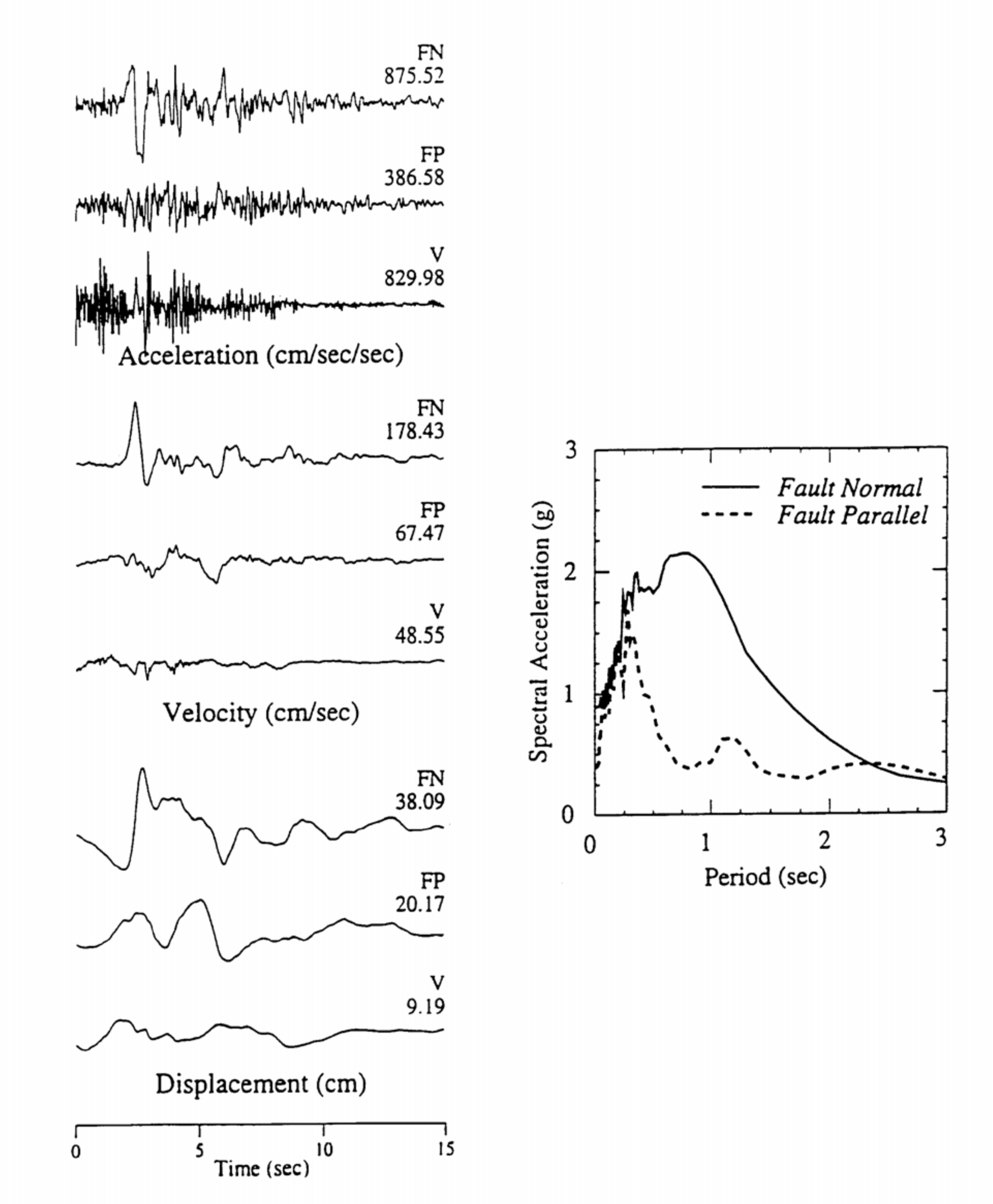

Figure 5-4. Time-histories and horizontal response spectra (5 percent damping) for the strike-normal and strike-parallel components of ground motion for the Rinaldi recording obtained 4.5 miles (7.5 km) from the fault rupture during the 1994 Northridge, California, earthquake (Somerville 1997)

for a design return period) reflects the contribution of different earthquake magnitudes and distances to the probabilities of exceedance. Therefore, when the design response spectrum is probabilistically based, the PSHA should be deaggregated to define the relative contributions of different magnitudes and distances to the ground motion hazard. Furthermore, the deaggregation should be done for probability values or return periods that correspond to those of the design earthquake and for response spectral periods of vibration of significance for seismic structural response because the relative contributions of different magnitudes and distances may vary significantly with return period and period of vibration.

(2) Figure 5-5 illustrates deaggregation of seismic hazard at a site in the western United States located close to highly active faults. The variation in relative contributions of different magnitudes and distances with return period (RP) and period of vibration *T* is evident. In the example in Figure 5-5, if the design return period is 1,000 years and the periods of interest for structural response are short periods close to 0.3 sec, then the center lower panel of the figure indicates that contributions would be strongly centered about magnitude 6.5 and distances within 10 km. Therefore this magnitude and distance range should be considered representative in selecting time-histories and defining strong motion duration.

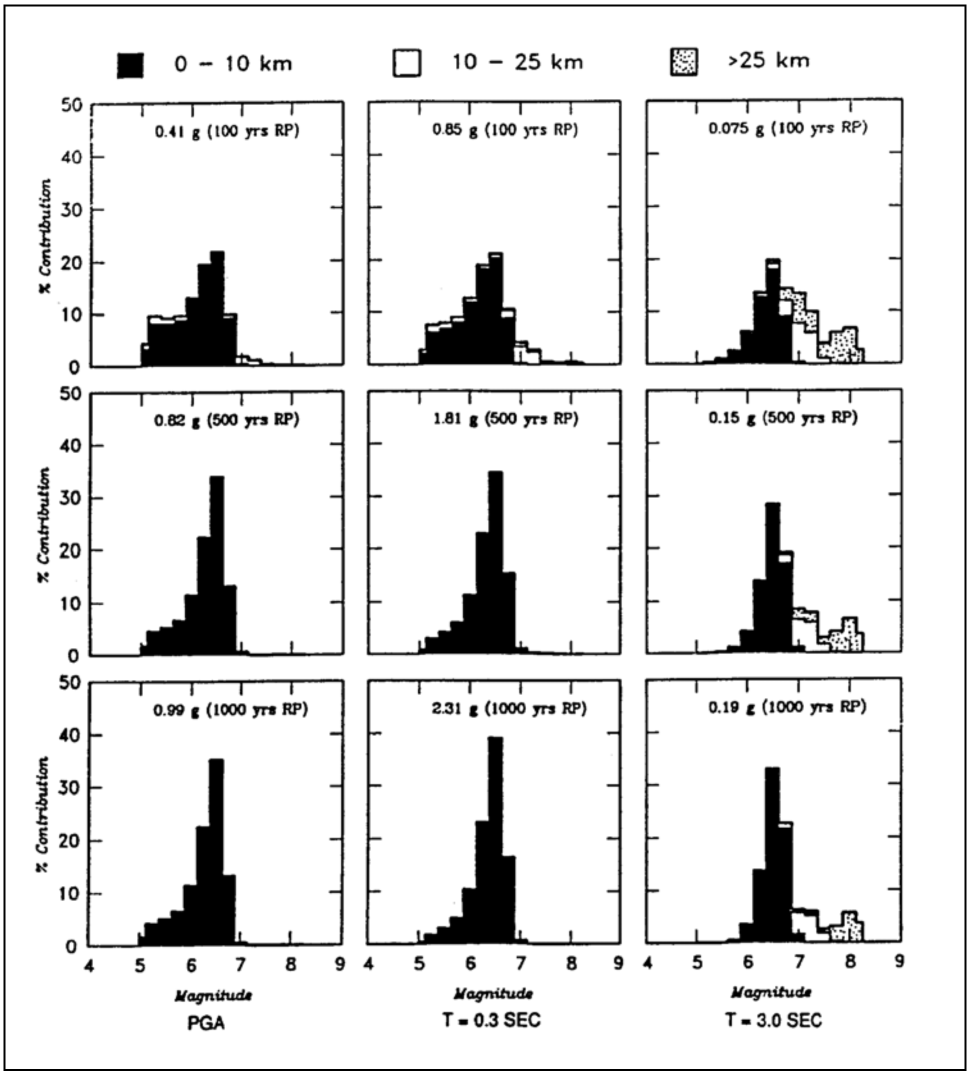

Figure 5-5. Example of deaggregation of seismic hazard from a probabilistic seismic hazard analysis in the western United States

(3) Figure 5-6 illustrates deaggregation of seismic hazard at a site in the eastern United States located in a low-seismicity area in which seismic sources are characterized as source zones. In this example, for a design return period of 2,500 years, earthquake magnitudes in the range of about 5 to 6.5 and distances in the range of 0 to 50 km dominate contributions to a 0.3-sec hazard. In this case, it would be appropriate to select a magnitude of about 5.5 to 6 and a distance of about 15 km as the average magnitude and distance to consider for selecting (or synthesizing) time-history records.

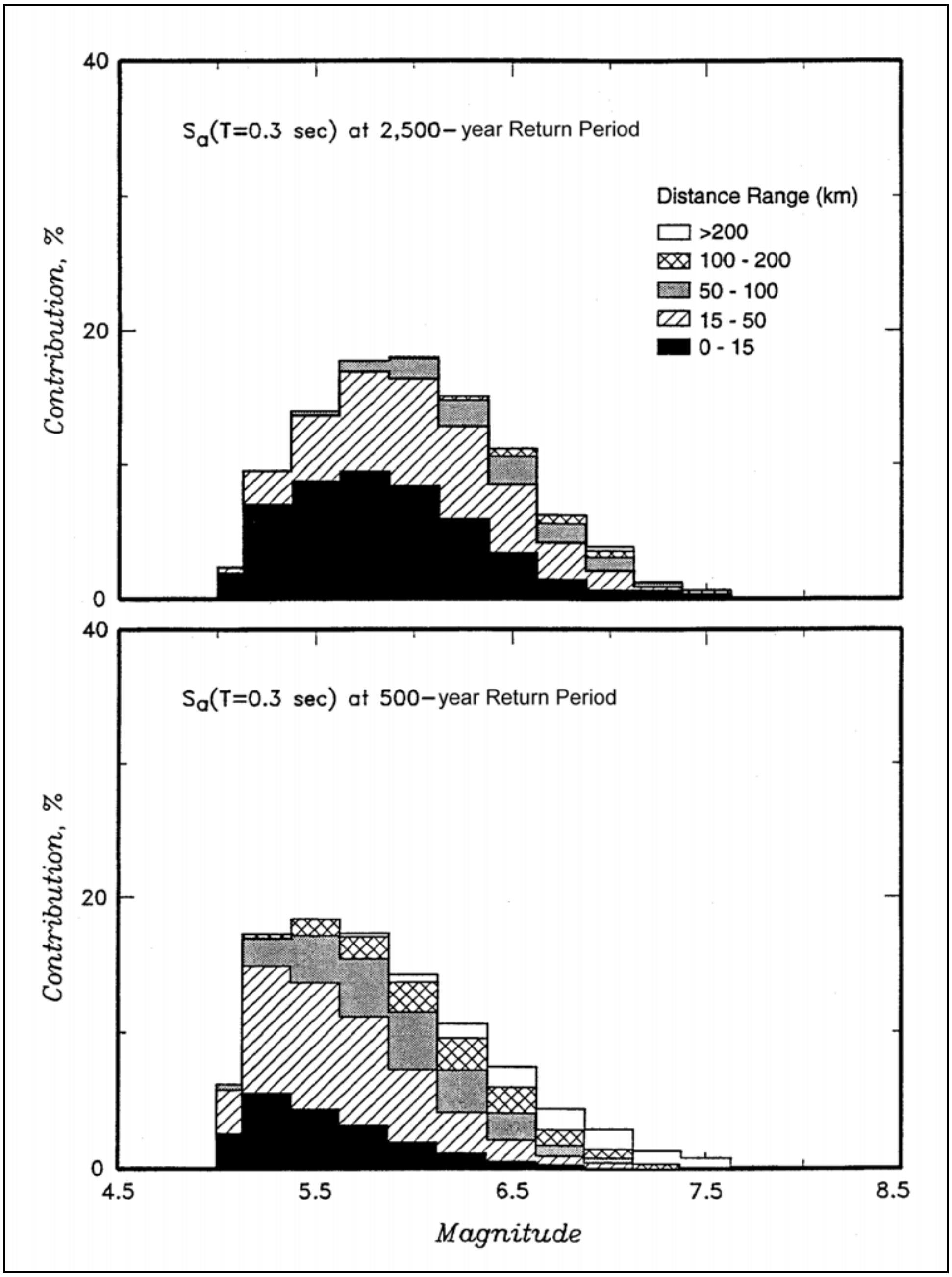

Figure 5-6. Example of deaggregation of seismic hazard from a probabilistic seismic hazard analysis in the eastern United States

(4) Note that for probabilistic analyses at some sites, for a given return period, relative magnitude and distance contributions may vary significantly with period of vibration within the period range of significance for structural response (generally the influences of larger magnitudes and larger distances increase with increasing period of vibration). Where this is the case, consideration should be given to selecting different time-history sets for the earthquakes contributing to different parts of the period range. However, this variation of magnitude and distance contributions with period of vibration is less significant for stiff concrete hydraulic structures having low fundamental periods of vibration than for long-period structures. In some other cases, deaggregation of a PSHA may show a distinct bimodal contribution to the hazard for certain periods of vibration (e.g., major contributions from both nearby moderate-magnitude earthquakes and distant large-magnitude earthquakes). In these cases, it may be appropriate to select time-history sets for both earthquakes. Again, this type of result of a PSHA is usually seen for long periods of vibration and not the shorter periods that are typical of concrete hydraulic structures.

5-4. Simple Scaling Approach to Final Development of Acceleration Time-Histories

a. General. Time-histories to be considered for seismic analysis are those initially selected as described in paragraph 5-3. Using the simple scaling approach, each selected time-history is then scaled by a single factor so that the response spectrum of the scaled time-history is approximately at the level of the design smooth response spectrum in the period range of significance to structural response. Since a recorded (or simulated recorded) time-history typically contains peaks and valleys at different periods, it is likely that, after scaling, the degree of agreement of the smooth design spectrum and the spectrum of the scaled time-history will vary greatly with period. In the following subparagraphs, guidelines are presented for the minimum number of time-histories to be used for seismic analysis and the degree of agreement of the fit of spectra of the time-histories to the design spectrum.

b. Number of time-histories.

(1) Time-histories for use in linear dynamic analysis. For use in linear dynamic analysis, at least three time-histories (for each component of motion) should be used for each design earthquake.

(2) Time-histories for use in nonlinear dynamic analysis. For use in nonlinear dynamic analysis, at least five time-histories should be used (for each component of motion) for each design earthquake. Fewer time-histories are required for linear dynamic analysis than for nonlinear analysis because the dynamic response of a linear structure is determined largely by the response spectral content of the motion, whereas the response of a nonlinear structure may be importantly influenced by the time domain character of the time-history (e.g., shape, sequence, and number of pulses) in addition to the response spectrum characteristics. Since these time domain characteristics may vary greatly for time-histories having similar spectral content, more time-histories are required for nonlinear analysis to capture the variability in response. If the nonlinear response is found to be significantly sensitive to the time-history characteristics for the records selected, then the set of time-histories should be expanded.

c. Degree of spectrum fit of time-histories used with the design spectrum.

(1) Spectrum fit for individual time-histories. Each time-history should be scaled to the approximate level of the design response spectrum. As a guideline, the scaling factor should be initially selected such that the sum of the differences (calculated period by period) of the logarithms of the spectral accelerations of the scaled time-history and the logarithms of the design response spectrum is approximately equal to zero over the period range of significance to structural response. Although it is desirable to implement this guideline quantitatively, it is also satisfactory to implement it qualitatively by obtaining an average, visual fit of the spectrum of the scaled time-history to the design response spectrum. Note that the scaling and resulting

spectrum fit for individual time-histories may have to be adjusted in order to satisfy the aggregate fit requirements stated in (2) below.

(2) Aggregate spectrum fit requirements for time-history sets. For each component of motion used in the analysis, a mean spectrum of the individual spectra of the time-histories should be calculated period by period. The mean spectrum should not be more than 15 percent lower than the design response spectrum at any period in the defined period range of significance to structural response. Furthermore, over the defined period range of significance, the average of the ratios of the mean spectrum to the design spectrum should be equal to or greater than unity. Figure 5-7 illustrates a comparison of spectra of four scaled time-histories with a design spectrum that satisfies these aggregate fit requirements over the period range 0 to 0.6 sec (selected in this example as the period range of significance to structural response). The individual time-histories in this example were initially scaled according to the quantitative guideline stated in paragraph (1) above, and the scaling factors were then adjusted for the time-histories to meet the aggregate fit requirements of this paragraph.

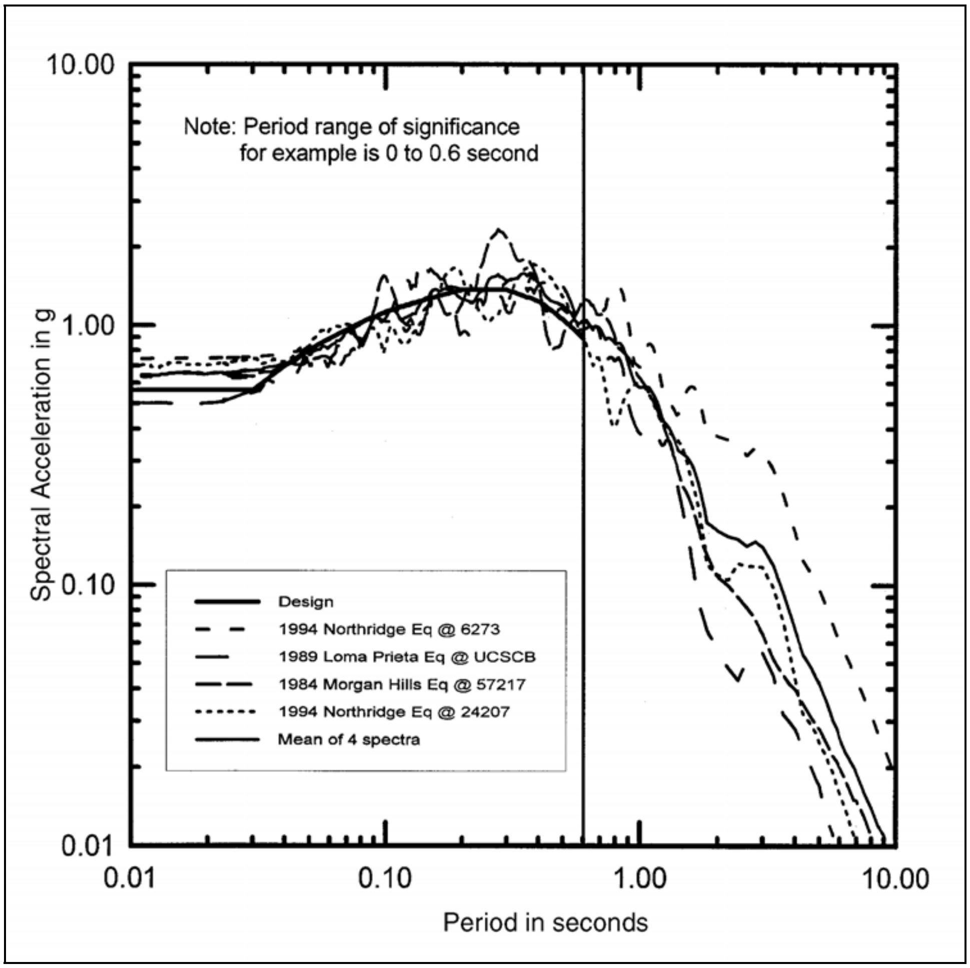

Figure 5-7. Illustrative comparison of spectra for four scaled time-histories and the mean spectrum with a designed spectrum in a period range of significance to structural response

d. Considerations for dynamic analysis for multiple components of motion. The criteria presented in *c*(2) above for the degree of spectrum fit are applicable for a single component of motion from each ground motion record used in the analysis. There are additional considerations and alternatives when the seismic analysis requires more than one component of motion (i.e., 1 horizontal + 1 vertical; 2 horizontal; or 2 horizontal + 1 vertical components). In these cases, the following alternatives may be considered for scaling the different components of each ground motion record.

(1) Use same scaling factors for each component. With this approach, the scaling factors for the component that is most important to response (e.g., the horizontal component to be applied perpendicular to the axis of a dam) are applied to the selected time-histories such that the fit criteria in *c*(2) above are satisfied. The same scaling factors are then used for the other component(s) of motion required for the analysis. This approach has the advantage that the relative amplitudes of different components of the same record are preserved. However, the aggregate fit to the design spectrum for the other component(s) of motion may be poorer than the fit for the primary component (i.e., aggregate fit in *c*(2) above may not be satisfied for the other components). This approach may be considered when structural response is dominated by one component of motion. The aggregate fit for the other components should be examined by the seismic analyst with respect to its influence on structural response. If the structural response is not adequately captured, additional scaling of the time-histories should be performed.

(2) Using different scaling factors for each component. With this approach, different scaling factors are applied as required to each component of motion. The aggregate fit criteria stated in *c*(2) are applied to each component. This approach has the advantage that for each component of motion, a good aggregate spectral fit will be obtained. The disadvantage is that the relative amplitudes of different components of the same record are not preserved. This approach is acceptable but is less desirable than the approach of alternative (1).

5-5. Spectrum-Matching Approach to Final Development of Acceleration Time-Histories

a. General. Using the time-histories selected as described in paragraph 5-3, the first step is to scale the time-histories to be the approximate level of the design response spectrum in the period range of greatest significance to structural response. This step is the same as that described in paragraph 5-4*c*(1) for the scaling approach. Then, the spectral content of the time-histories is modified to provide a close match to the design spectrum using spectrum-matching techniques. The following subparagraphs present guidelines for the number of time-histories to be used for seismic analysis and the degree of agreement of the fit of the spectra of the time-histories with the design spectrum, describe different types of spectrum matching methods and periods of vibration to be used for matching, and summarize the advantages and disadvantages of the spectrum matching approach versus the simple scaling approach.

b. Number of time-histories.

(1) Time-histories for use in linear dynamic analysis. Because the response of a structure in a linear dynamic analysis is determined by the spectral content of the time-history and because it is possible to obtain a very close fit to the design spectrum using spectrum-matching methods, it is sufficient to have a single time-history for each component of motion for each design earthquake.

(2) Time-histories for use in nonlinear dynamic analysis. Because the nonlinear structural response may be strongly affected by the time-domain character of the time-histories even if the spectra of different time-histories are nearly identical, the requirements for numbers of time-histories are the same as for the simple scaling approach. At least five time-histories (for each component of motion) should be used for each design earthquake.

c. Degree of spectrum fit of time-histories used with design spectrum. When multiple time-histories are used (for a single component) for each design earthquake, a mean spectrum of the individual spectra of time-histories should be calculated. The requirements for the fit of this mean spectrum are the same as for the simple scaling approach stated in paragraph 5-4*c*(2): the mean spectrum should not be more than 15 percent lower than the design response spectrum in the period range of significance to structural responses; and the average of the ratios of the mean spectrum to the design spectrum should be equal to or greater than unity over this same period range. If a single time-history is used (for a single component), then the degree of fit of the spectrum of this time-history should be the same as stated in this paragraph for the mean of the spectra of multiple time-histories.

d. Considerations for dynamic analysis for multiple components of motion. In cases where two or three components of motion are needed for dynamic analysis, the objective for each component is to have a close match to the design horizontal and vertical spectrum. Therefore, for each component, time-histories should initially be scaled to the approximate level of the design spectrum as stated in *a* above and then spectrum matching carried out to provide the degree of fit stated in paragraph *c* above.

e. Spectrum-matching methods.

(1) Spectrum matching methods include methods in which the time-history adjustments are made in the time domain and those in which the adjustments are made in the frequency domain. These methods are described and illustrated in Appendix C. As illustrated therein, either method is capable of producing design time-histories that not only have spectra that are a close match to a design response spectrum but also have time-histories that, in most cases, maintain fairly well the basic time-domain character of the recorded or simulated recorded time-histories with respect to shape, sequence, and number of pulses.

(2) To minimize changes to the time-domain character of the recorded time-histories when using the spectrum-matching approach, it is desirable that

- The overall shape of the spectrum of the recorded (or simulated recorded) time-history not differ greatly from the shape of the design response spectrum.

- As stated in *a* above, the time-history initially be scaled so that its spectrum is at the approximate level of the design spectrum to minimize the changes that occur to the time-history during the subsequent spectrum-matching process.

Figures 5-8 and 5-9 are examples of a design time-history developed using the spectrum-matching approach. Shown in these figures are the scaled time-histories (acceleration time-history and the corresponding velocity and displacement time-histories) before and after spectrum matching (Figure 5-8) and the corresponding acceleration response spectrum compared with the design response spectrum (Figure 5-9). The close spectrum match can be noted as well as the similar appearance of the time-histories before and after spectrum matching. As shown in Figure 5-9, spectrum matching was carried out in the period range 0 to 2 sec for this example. Appendix D presents an examination of the effect of the spectrum-matching process on several ground motion characteristics for ten time-histories. The appendix illustrates that the process is capable of producing time-histories having characteristics that generally do not differ greatly from those of scaled recorded motions.

f. Periods of vibration for spectrum-matching. It is important that spectrum matching be carried out for a sufficiently fine grid of periods or frequencies of vibration that the response spectrum of a matched time-history is also smooth and nearly the same as the design spectrum at intervening periods. A recommended

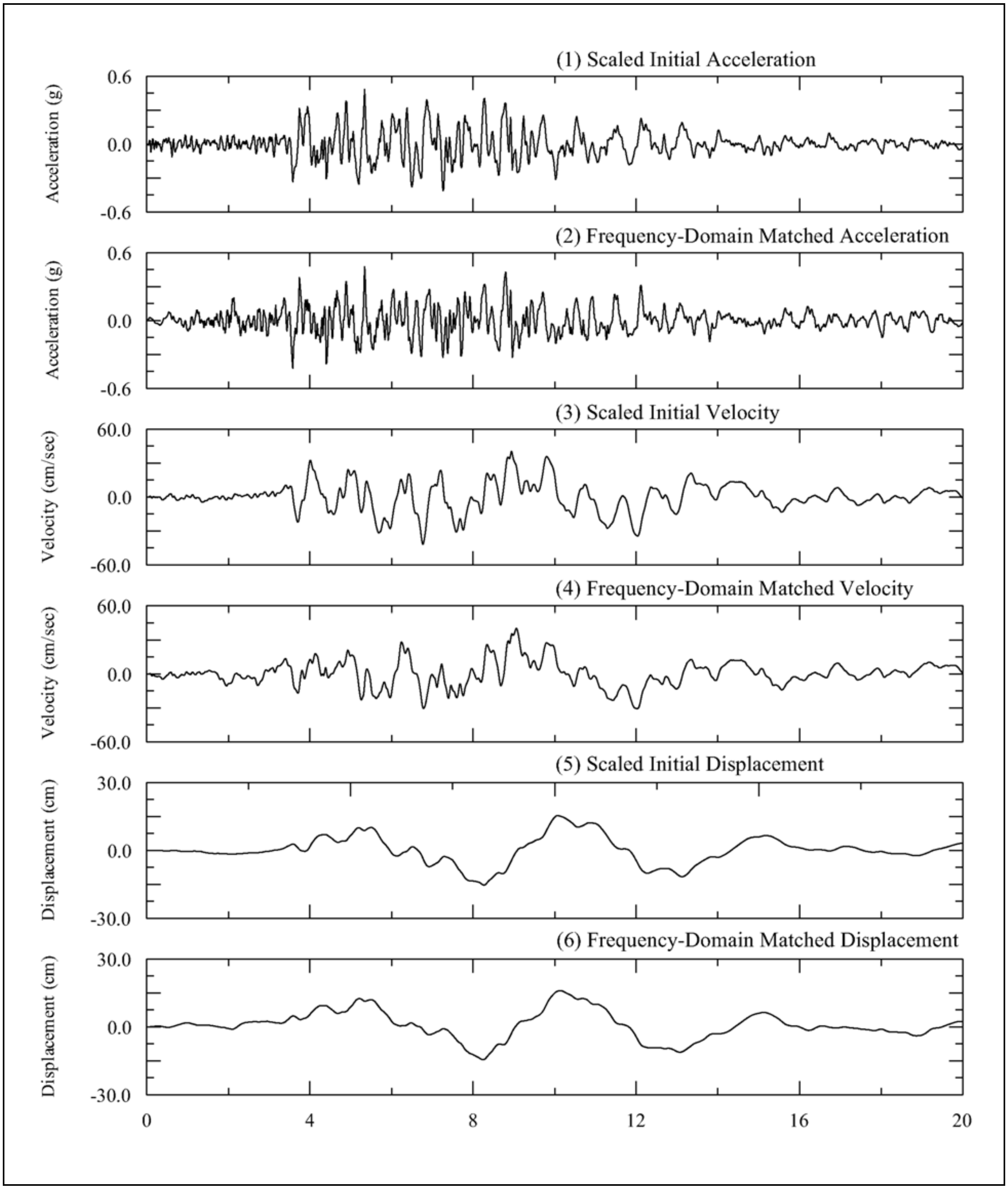

Figure 5-8. Comparisons of scaled time-histories from the 1971 San Fernando earthquake at Griffith Park (270E) to the frequency-domain matched time-histories

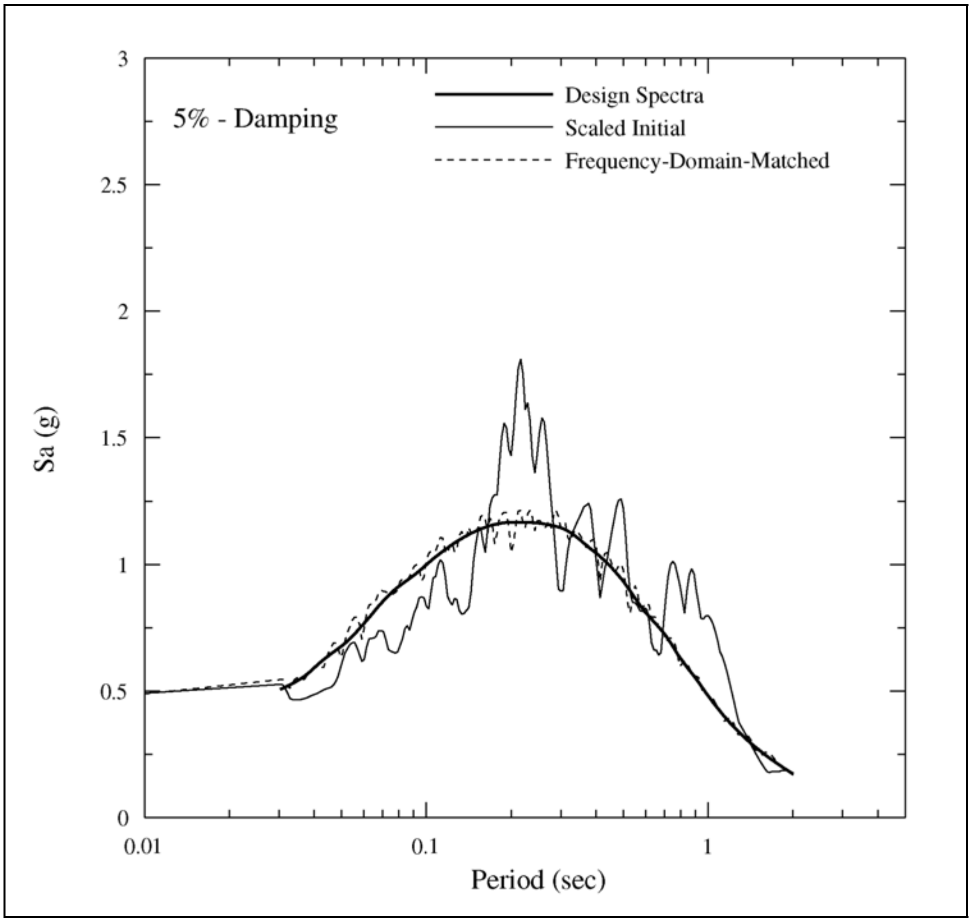

Figure 5-9. Comparisons of response spectra from the scaled 1971 San Fernando earthquake at Griffith Partk (270E) and the frequency-domain matched acceleration time-history

grid of frequencies for spectrum matching to achieve this objective is 120 frequencies per decade (equally spaced on the log frequency axis).

g. Relative advantages and disadvantages of spectrum matching and simple scaling approaches for developing design time-histories. The simple scaling approach has the advantage that the time-histories are truly "natural" and represent time-domain and spectral characteristics of actual recordings (or simulated recordings), except for the scaling of the records. On the other hand, some of the "natural" quality is lost if different components of the same record are scaled by different factors (paragraph 5-4*d*). The spectrum matching approach has the advantage that fewer time-histories are required, at least for linear analysis. The disadvantage is that the time-domain character of the record is altered to some degree through the spectrum-matching process. The results in Appendices C and D indicate that, if the spectra of the selected scaled time-histories do not differ greatly from the design spectrum (i.e., spectral peaks and valleys of the time-histories oscillate about the design spectrum) then the changes induced by spectrum matching on the time-domain character of the time-histories are generally fairly small. Appendix D also indicates that the spectrum-matching process does not greatly change the energy of a time-history, if the spectrum of the scaled time-histories does not differ too much from the design spectrum. In summary, both the simple scaling approach and the spectrum-matching approach are acceptable provided that the guidelines for time-history selection and development presented in this chapter are followed.

5-6. Modifying Time-Histories for Site Response Effects

a. General. The two approaches for accounting for site soil response effects at a project site on acceleration time-histories are as follows:

- Selecting and developing the design time-histories to be representative of the type of soil conditions present at the project site using the procedures presented in the previous paragraphs of this chapter.

- Selecting and developing design time-histories for rock conditions underlying a site (using the procedures presented in the previous paragraphs) and then modifying the time-histories by propagating them through an analytical model of the site soil profile.

Either approach can be used; the choice of the approach depends on the subsurface conditions at a site and the preferences of the seismic analyst and principal design engineer. If deep and stiff soil conditions exist at a site, the depth to bedrock is not well defined, and the dynamic properties of the soil are not well defined, then generally approach 1 would be preferred. If a well-defined bedrock exists beneath a site and the stratigraphy and dynamic properties of the site can be adequately characterized, then generally approach 2 would be preferred. Approach 1 is described in the preceding paragraphs of this chapter. The additional steps involved in approach 2 are summarized below. It is noted that in many cases it may be appropriate to carry out the analyses in approach 2 as part of the dynamic analysis of the structure, rather than as an analysis only to modify the bedrock time-histories for the site soil conditions. In such cases, the dynamic analysis is of the modeled soil and structure system to the design rock time-history (soil-structure-interaction analysis).

b. Conducting site soil response analyses. Conducting an analysis of the response of a site soil profile to an input design rock motion time-history is schematically illustrated in Figure 5-10 and is summarized below.

(1) Modeling the soil profile. The stratigraphy and dynamic properties (dynamic moduli and damping characteristics) of the soil profile are modeled. If the soil depth is reasonably constant beneath the structure and the soil layers and ground surface reasonably flat, then a one-dimensional site-response soil model and analysis method can be used as illustrated in Figure 5-10. Two- or three-dimensional models of the site soils can be used where these conditions are not met. Unless the soil properties are very well constrained by a field and laboratory testing program, a range of properties should be defined for the soil layers to account for the uncertainties in the properties.

(2) Analysis and calculation of top-of-soil time-histories. The design bedrock time-histories are input to the soil model, the response of the model is calculated, and the corresponding top-of-soil time-histories are obtained. The rock motions are assigned to a hypothetical rock outcrop at the site rather than to the rock at depth beneath the soil column. This assignment is made because actual rock motion recordings are usually obtained at the ground surface rather than at depth and, unless the rock is rigid, the rock motion beneath a soil column will differ from the rock outcrop motion. Analysis techniques to be used (and corresponding models of soil properties) should incorporate nonlinear soil behavior either through the equivalent linear method or true nonlinear analysis methods. Computer codes that may be considered for one-dimensional analysis include equivalent linear codes SHAKE (Schnabel, Seed, and Lysmer 1972; Idriss and Sun 1992) or WESHAKE (Sykora, Wahl, and Wallace 1992); and nonlinear codes DESRA-2 (Lee and Finn 1978), DESRA-MUSC (Qiu 1998), SUMDES (Li, Wang, and Shen 1992), MARDES (Chang et al. 1990) D-MOD (Matasovic 1993), and TESS (Pyke 1992). Computer codes that may be considered for 2- or 3-D analyses include equivalent linear codes FLUSH (2-D) (Lysmer et al. 1975), QUAD4M (Hudson, Idriss, and Beikae 1994), and SASSI (2-D or 3-D) (Lysmer et al. 1991) (in SASSI, equivalent linear analysis is possible only through successive external

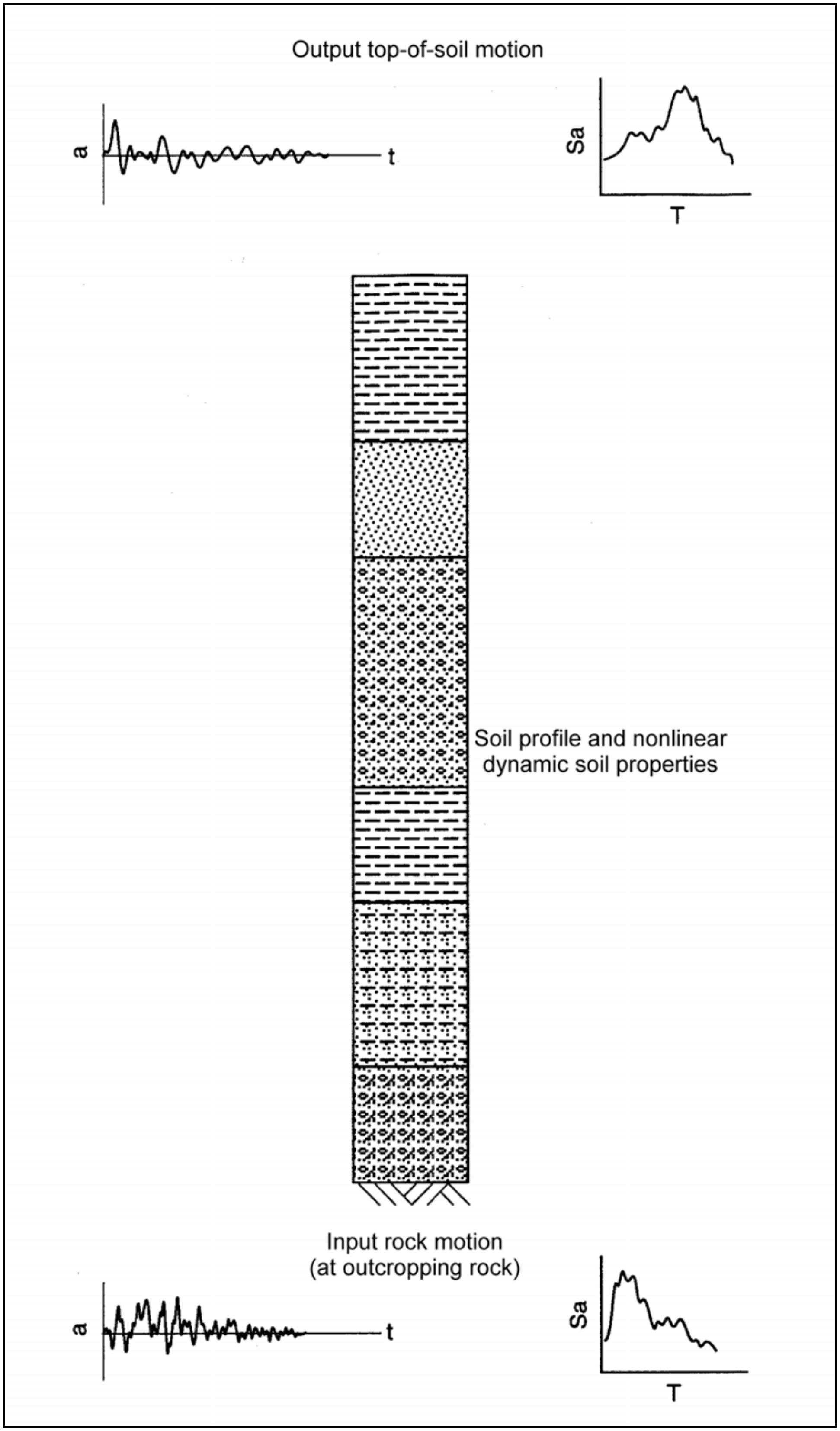

Figure 5-10. Schematic of one-dimensional site response analysis

adjustment of soil properties and iterative analysis); and nonlinear codes FLAC (Itasca 1998; Wang and Makdisi 1999), and TENSI-MUSC (Martin 1998). Analyses should be carried out for a range of soil dynamic properties unless the properties are very well constrained as stated in the preceding paragraph. Soil time-histories obtained from the analyses should be baseline-corrected before using them for dynamic structural analysis.

c. Conducting other types of analyses for local site effects. Conceptually, a 3-D analysis could be carried out to determine the effect of an irregular surface topography on the ground motions, such as at an arch dam site. The topographic effects could include amplification and deamplification, differences in frequency content, and out-of-phase arrivals of the ground motions at different locations of the interface of the ground and the structure. At present, such analyses are not commonly performed because realistic modeling of the site with the irregular topography and geology would be either too costly or not well constrained by data on the characteristics of the geologic materials.